Single hole spectroscopic strength in ^{98}Ru through the ^{99}Ru(d,t) reaction

M. R. D. Rodrigues,[1] T. Borello-Lewin,[1] L. B. Horodynski-Matsushigue,[1] J. L. M. Duarte,[1] C. L. Rodrigues,[1] M. D. L. Barbosa,[1] G. M. Ukita,[1,2] and G. B. da Silva[1]

[1]*Instituto de Física, Universidade de São Paulo, Caixa Postal 66318, CEP 05389-970, São Paulo, SP, Brazil*

[2]*Faculdade de Psicologia, Universidade de Santo Amaro, Rua Professor Enéas da Siqueira Neto, 340, CEP 04829-300, São Paulo, SP, Brazil*

(Received 25 April 2002; published 27 September 2002)

The ^{99}Ru$(d,t)^{98}$Ru reaction was measured for the first time at 16 MeV incident energy with the São Paulo Pelletron-Enge-spectrograph facility employing the nuclear emulsion technique. In all, up to 3.5 MeV, 23 levels were detected, eight of them new; angular distributions are presented for all of them. Least squares fits of distorted wave Born approximation one-neutron pickup predictions to the rather well structured experimental angular distributions enabled the determination of l transfers and of the corresponding spectroscopic factors for 19 of these states, some being tentative attributions. Only transfers of $l=0$, 2, and 4 were observed. Several states were populated through single l transfers. A pure $l=2$ transfer is associated with the 2_1^+ level and with several other states which are considered collective, as well as with the (4^+) state at 2.277 MeV, which presents the highest spectroscopic strength. Considering five valence neutrons above the $N=50$ core, only 41% of the spectroscopic strength expected for ^{99}Ru was detected.

DOI: 10.1103/PhysRevC.66.034314 PACS number(s): 21.10.Jx, 25.45.Hi, 27.60.+j

I. INTRODUCTION

One-nucleon transfer reactions are powerful experimental tools to reveal single-particle and -hole aspects of the residual nucleus with respect to the ground state of the target. They have also been employed to obtain shell model occupancy and vacancy information for the ground state of the target nucleus through the analysis of summed spectroscopic strengths [1,2]. However, studies of this kind have more frequently focused on reactions in which the initial nucleus is even-even, due to the increased complexity expected for data on odd-even or odd-odd targets. In fact, with initial spins $J \neq 0$, an incoherent superposition of several angular momenta l are, in general, allowed. On the other hand, it is interesting to note that, even for the states of even-even nuclei lying lowest in energy and usually interpreted as collective structures, the analysis of one-neutron or one-proton stripping or pickup reactions could provide insight into their microscopic constituents. In particular, these studies could prove important in disclosing clues for the interpretation of isotope and/or isotone chains in transitional mass regions. In the intriguing region around $A=100$, the São Paulo Nuclear Spectroscopy Group has been involved in the experimental study of ruthenium isotopes through (d,p) [2–4] and (d,t) [1] reactions on even targets. Along the isotopic chain, the more recent focus of interest in this line of investigation is the reactions which start from ^{99,101}Ru, the only stable odd isotopes. The previous studies of this kind were the ^{101}Ru(p,d) [5] and ^{101}Ru(d,t) [6] reactions which demonstrated that rather structured experimental angular distributions, characteristic of one-step direct excitation with at most two l transfers, are associated with the majority of the ^{100}Ru states populated. The present work increases the knowledge of the region through spectroscopic results for the ^{99}Ru$(d,t)^{98}$Ru reaction, formerly not reported in the literature. The mapping of the microscopic characteristics of ^{98}Ru, described as a hole in the ^{99}Ru ground state, may thus be employed as a further tool in the understanding of differences between odd and even Ru nuclei pointed out previously [1].

II. EXPERIMENTAL PROCEDURE

The thin [17.8(3) μg/cm^2] ^{99}Ru target was bombarded by 16 MeV deuterons from the São Paulo Pelletron accelerator. This ^{99}Ru film was prepared by electron bombardment evaporation of metallic ^{99}Ru powder, isotopically enriched to 97.6%, onto a thin carbon backing. The tritons produced in the reaction were momentum analyzed by the Enge magnetic spectrograph and detected in nuclear emulsion (Fuji G6B, 50 μm thick). Spectra were taken at eight judiciously chosen scattering angles, from $\Theta_{\rm lab}=8°$ to $\Theta_{\rm lab}=40°$. After processing, the exposed emulsion was scanned in strips of 200 μm across the plates. An energy resolution of 7 keV was achieved. Figure 1 shows the triton spectra corresponding to $\Theta_{\rm lab}=10°$ and $\Theta_{\rm lab}=35°$, which can be regarded as typical of the spectra measured at other angles.

The total number of projectiles corresponding to each spectrum was obtained with the help of a calibrated current integrator connected to an aligned Faraday cup with electron suppression. The beam direction was monitored continuously. The relative normalization of the spectra was thus obtained, while the absolute normalization of the cross sections was referred to optical model predictions for the elastic scattering of deuterons on the same target, measured under similar conditions. The elastic spectra were measured at five laboratory scattering angles from 30° to 70°. Considering the differences in the predictions for three families of optical potentials [7–9] and the contributions due to target nonuniformity, plate scanning, and statistics to the systematic uncertainty affecting the cross sections, a maximum scale uncertainty of 8% is estimated for the absolute values.

The parameters of Perey and Perey [7], with the addition of the spin orbit term suggested by Lohr and Haeberli [8], were chosen for both the absolute normalization of the elas-

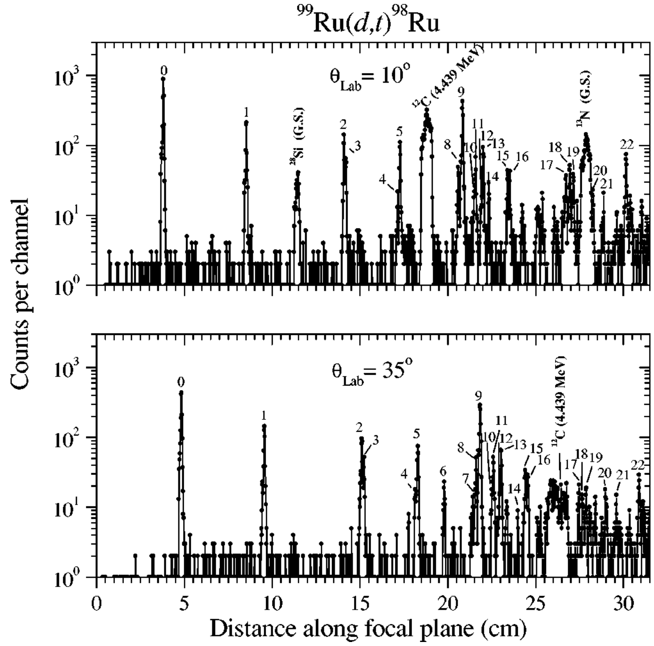


FIG. 1. Spectra of tritons at $\Theta_{lab}=10°$ and $\Theta_{lab}=35°$.

tic cross section and the generation of the distorted incident waves in the reaction analysis and are shown in Table I. The optical model parameters of Becchetti and Greenlees [9] for describing the outgoing triton channel and the geometrical parameters for the bound neutron are also shown in Table I. The distorted wave Born approximation (DWBA) calculations were performed with the code DWUCK4 [10] with the usual corrections to account for finite range and nonlocality effects. The DWBA predictions were fitted to the experimental angular distributions through a χ^2 minimum procedure. Incoherent l admixtures are allowed for each state, since the neutron, with orbital angular momentum l and total spin j, is transferred from the odd ^{99}Ru $5/2^+$ ground state. The neutron single-particle orbitals considered were those of the $N=50$–82 shell. For $l=2$ transfers, both $2d_{5/2}$ and $2d_{3/2}$ are accessible and the $2d_{5/2}$ orbital was arbitrarily supposed. For each of the transferred orbital angular momenta l, the fitting procedure allowed for the determination of the respective spectroscopic strength C^2S_{lj} through the fitting factors a_{lj}, according to the relations

$$\sigma_{\exp}(\theta)=\sum_{l,j} a_{lj}\sigma_{lj}^{DW}(\theta)$$

and

$$C^2S_{lj}=\frac{2j+1}{3.33}a_{lj}.$$

The factor 3.33 is due to the overlap of the triton and deuteron wave functions, taken, respectively, in the Irving-Gunn and Hulthén descriptions [11].

III. RESULTS

The excitation energies presented in Table II are the averages of the energies determined for each level in the several spectra after applying the calibration [12] of the spectrograph. Excitation energy values are given whenever a level was clearly identified for at least five angles. The dispersion of the individual energy values around their mean is typically less than 2 keV. Below 3 MeV, the systematic uncertainty is estimated to be less than 2 keV, increasing above the region of peak at 17, to about 5 keV. The present values of excitation energies are in excellent agreement with the values of the recent Nuclear Data Sheets (NDS) compilation [13]. The exception is the state at 2.277 MeV, here associated with the level at 2.285 MeV, since this adopted level, detected by proton inelastic scattering measurements, is accompanied by an uncertainty of 10 keV. The states at 2.365, 2.373, 2.409, 3.020, 3.046, 3.209 (possible doublet), 3.284, and 3.441 MeV had not been observed before, but could be established with certainty through the present reaction.

Figure 2 shows the experimental angular distributions for those transitions for which the cross section was measured, at five angles or more. The relative experimental uncertainties, represented by the bars, include contributions due to plate scanning, background subtraction, statistical deviations, and relative normalization. Least squares fits of DWBA predictions to the experimental angular distributions are also shown in Fig. 2 whenever an assignment of l was attempted. Information on the values of the transferred orbital angular momenta, limits for the total angular momentum J, the parity, and the extracted spectroscopic factors for each level can be found in Table II. In this table, the uncertainties stated for

TABLE I. Optical potential parameters employed in the analysis of the reaction ^{99}Ru$(d,t)^{98}$Ru.

	Potential	V_R (MeV)	r_R (fm)	a_R (fm)	W (MeV)	r_W (fm)	a_W (fm)	W_D (MeV)	r_D (fm)	a_D (fm)	r_c (fm)	V_{so} (MeV)	r_{so} (fm)	a_{so} (fm)
Entrance channel deuterons	PP[a]	96.50	1.15	0.81				18.24	1.34	0.68	1.15	7.00	0.75	0.50
Bound neutron	BG[b]	fitted	1.17	0.75								$\lambda_{SO}=25$		
Exit channel tritons	BG[b]	164.35–0.17E	1.20	0.72	34.78–0.33E	1.40	0.84				1.30	2.50	1.20	0.72

[a]Reference [7].
[b]Reference [9].

TABLE II. Experimental results for ^{98}Ru, through the ^{99}Ru(d,t) reaction, in comparison with adopted levels of NDS (Ref. [13]).

	Present work					NDS[a]	
Peak	E_{exc} (MeV)	l	j	J^{π}	S_{lj}	E_{exc} (MeV)	J^{π}
0	0.000	2	5/2	0^+–5^+	0.339(7)	0.000 00	0^+
1	0.651	2	5/2	0^+–5^+	0.130(3)	0.652 44(4)	2^+
						1.322 14(6)	0^+
2	1.397	2	5/2	0^+–5^+	0.127(5)	1.397 81(5)	4^+
3	1.415	2	5/2	2^+–3^+	0.037(6)	1.414 29(4)	2^+
		0	1/2		0.012(2)		
4	1.797	2	5/2	2^+–3^+	0.009(2)	1.796 96(5)	3^+
		0	1/2		0.0041(7)		
5	1.818	2	5/2	0^+–5^+	0.120(3)	1.817 22(6)	$(1,2)^+$
						1.953 4(3)	(3^+)
6	2.013	(2)	(5/2)	0^+–5^+	0.036(3)	2.012 70(5)	3^+
7	2.224	(4)	(7/2)	1^+–6^+	0.12(2)	2.222 51(7)	6^+
						2.241 4(3)	$(4^+,5^+,6^+)$
8	2.247	(2)	(5/2)	2^+–3^+	0.054(5)	2.245 9(3)	(1,2)
		(0)	(1/2)		0.0064(11)		
						2.266 50(6)	4^+
						2.2768(2)	(2^+)
9	2.277	2	5/2	0^+–5^+	0.675(15)	2.285(10)	(4^+)
10	2.365						
11	2.373						
12	2.409	(2)	(5/2)	0^+–5^+	0.018(2)		
13	2.429	(2)	(5/2)	2^+–3^+	0.105(6)	2.427 14(16)	(2^+)
		(0)	(1/2)		0.011(2)		
						2.4302(3)	
						2.435(10)	(3^-)
14	2.469	0	1/2	2^+–3^+	0.0099(8)	2.4676(10)	$(1,2^+)$
15	2.605	(2)	(5/2)	0^+–5^+	0.060(4)	2.6023(3)	
16	2.621					2.6192(10)	$(1,2^+)$
						2.656 51(7)	(5^-)
						2.659 62(7)	$(3^+,4)$
						2.7203(3)	(3)
						2.8092(2)	(2^+)
						2.8677(2)	(6^+)
17	3.020	(2)	(5/2)	0^+–5^+	0.040(3)		
18	3.046	0	1/2	2^+–3^+	0.022(1)		
						3.0649(3)	$(3,4^+)$
19	3.071	(2)	(5/2)	2^+–3^+	0.024(6)	3.0693(3)	
		(0)	(1/2)		0.020(2)		
						3.126 31(9)	8^+
						3.1793(10)	$(1,2^+)$
						3.190 20(9)	(7^-)
20	3.209						
						3.2454(3)	(6^+)
						3.2509(3)	
						3.2834(2)	$(7)^-$
21	3.284	(0)	(1/2)	2^+–3^+	0.013(1)		
						3.3668(10)	$(1,2^+)$
22	3.441	0	1/2	2^+–3^+	0.045(2)		
						3.5370(10)	$\leqslant 4$

[a]Reference [13].

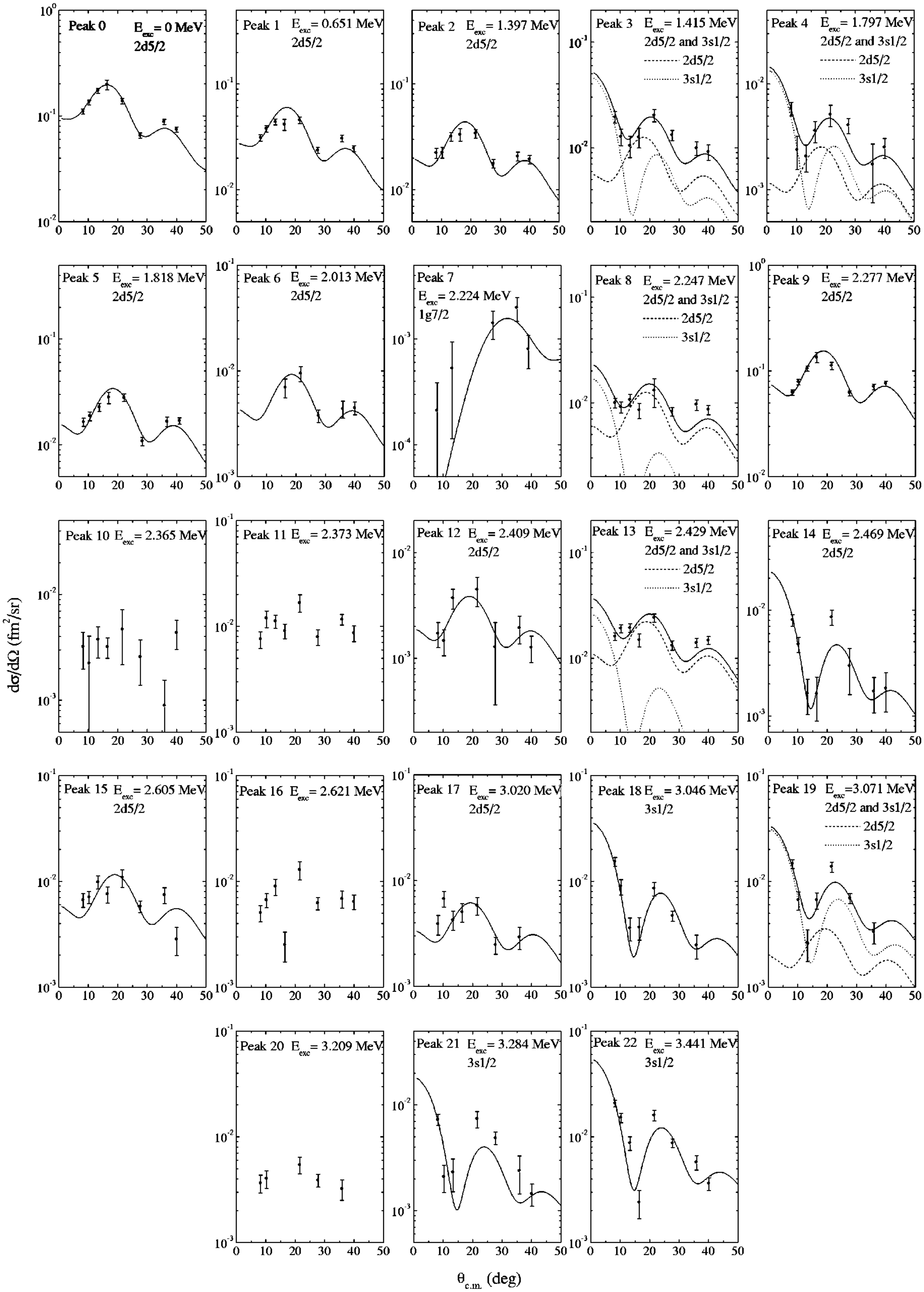
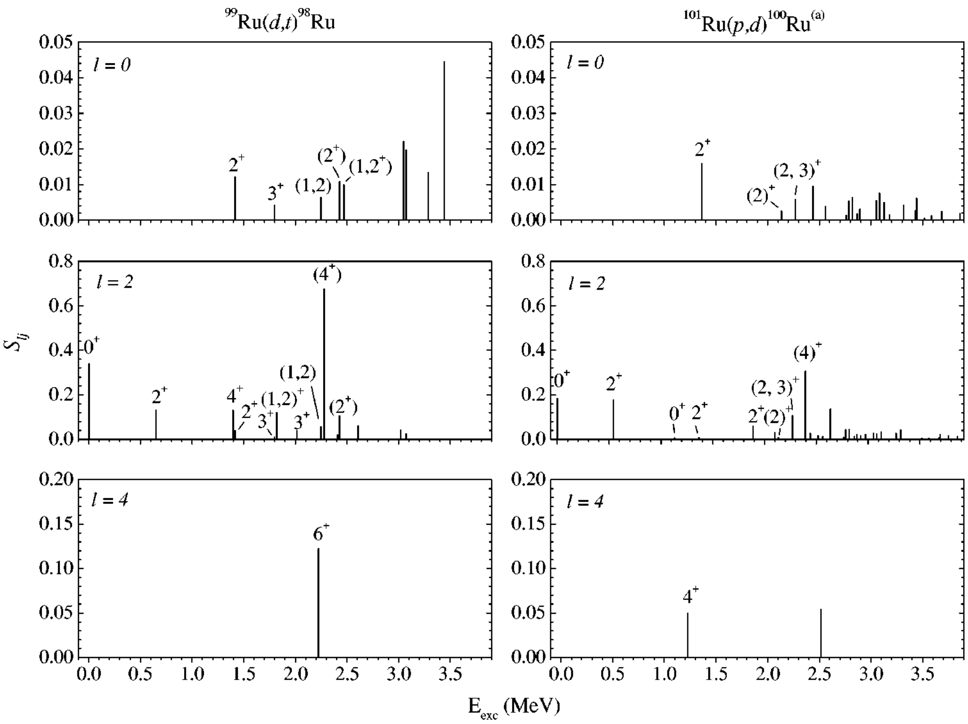


FIG. 2. Angular distributions associated with levels in ^{98}Ru through the (d,t) reaction.

the spectroscopic factors reflect only the relative uncertainties of the data points which comprise the experimental angular distribution.

Several single l transfers were observed, although incoherent l admixtures are allowed in the excitation of each state, except for the 0^+ states. In particular, it is to be noted that a pure $l=2$ transfer is associated with the first 2^+ state and also that states sometimes supposed to be multiphonon



^{a}reanalyzed

FIG. 3. Strength distributions for ^{98}Ru and ^{100}Ru.

[14,15] present well-structured angular distributions, being associated clearly with only one or two values of l transfers. In fact, the 4_1^+ at 1.397 MeV, the $(1,2)^+$ at 1.818 MeV, and the 6^+ at 2.224 MeV levels are excited by a single l transfer with spectroscopic intensities of the same order as that of the transition to the first 2^+ state. The 4_1^+ level is frequently interpreted as one of the two-phonon states. The other two states were taken by Kern *et al.* [14] as the 0_3^+ and 6_1^+ members of the three-phonon quintuplet. On the other hand, Giannatiempo *et al.* [15] interpreted the 1.818 MeV level as a 2^+ mixed symmetry state and the 6^+ as a three-phonon state, in an interacting boson model-2 (IBM-2) interpretation. Furthermore, other levels detected in the present transfer reaction with appreciable strength have been considered to be multiphonon states, such as the 1.415 MeV, 2_2^+ level [14,15], the 2.013 MeV, 3^+ level [15], proposed by Kern *et al.* [14] to be the 4_2^+ member, and the 2.247 MeV level, taken by Giannatiempo *et al.* [15] as the 2^+ state of the quintuplet of three phonons.

The strongest $l=2$ transition corresponds to the state (4^+) [13] at 2.277 MeV and deserves further discussion in comparison with ^{101}Ru$(p,d)^{100}$Ru [5] and ^{101}Ru$(d,t)^{100}$Ru [6] findings. No transitions of $l=5$ or of any other odd l value were characterized and the (3^-) [13] state, in principle, associated with the first octupolar excitation, was not detected.

IV. DISCUSSION

A. Spectroscopic strength distributions

Figure 3 presents the spectroscopic strength distributions, organized as a function of l transfer and excitation energy. Known and tentatively attributed spins [13] are marked. The strongest spectroscopic intensities are associated with $l=2$. Fourteen levels have been populated by $l=2$ transfer (half of them tentative) up to 3 MeV of excitation, showing a large fragmentation of this strength. For $l=0$ transfers, the strength is distributed among nine states above 1.4 MeV of excitation, four of them tentatively attributed. Only one tentative $l=4$ transition was detected. For further consideration, Fig. 3 also shows the spectroscopic strength distributions obtained in a reanalysis of the data of Peterson *et al.* [5] measured in the ^{101}Ru$(p,d)^{100}$Ru reaction. Aiming at a consistent comparison of the spectroscopic strength distributions in the Ru chain, the reanalysis here presented was based on the following arguments. Starting with the investigation of the influence of the unusual geometry of the bound neutron well employed in the work of Peterson *et al.* [5], a lack of Q dependence correction was also found in the DWBA calculations presented by the authors [5]. Furthermore, the high $l=0$ strength of the state at 2.268 MeV of excitation tabulated by the authors [5] seems to be due to a transcription error of a factor of 10 ($C^2S=0.10$ should be 0.01). A reanalysis of Peterson's data on ^{101}Ru$(p,d)^{100}$Ru [5] was subsequently carried out with the parameters of Becchetti and Greenlees [9] and Perey and Perey [7], in the entrance and exit channels, respectively, for the DWBA calculation. The geometry of the bound neutron well was taken from the real part of the optical potential of the neutron [9], as usual. It is interesting to note that the spectroscopic strengths extracted in this reanalysis revealed excellent agreement with the values formerly obtained by Sampaio [6] in the ^{101}Ru$(d,t)^{100}$Ru reaction. Comparing, with the help of Fig. 3, the strength distributions determined in the present work for ^{98}Ru and in the reanalysis of the data of Peterson *et al.* [5] for ^{100}Ru, a

TABLE III. Spectroscopic strength distribution for ^{99,101}Ru.

	Up to E_{exc} (MeV)	$3s_{1/2}$	$3p_{3/2}$	ΣG_{pick} $2d_{5/2}+2d_{3/2}$	$2f_{7/2}$	$1g_{7/2}$	Sum (occupancy)
^{99}Ru$(d,t)^{98}$Ru	3.5	0.14		1.77		0.12	2.04
^{101}Ru$(d,t)^{100}$Ru [a]	2.5	0.049		1.16		0.06	1.27
^{101}Ru$(p,d)^{100}$Ru [b]	3.9	0.24		1.94		0.23	2.41
^{101}Ru$(p,d)^{100}$Ru [c]	3.9	0.093	0.0005	1.42	0.012	0.10	1.63

[a]Reference [6].
[b]Reference [5].
[c]Reanalysis of the data of Peterson *et al.* (Ref. [5]).

global correspondence is verified. The $l=0$ transitions are fractionated and appear above 1.3 MeV of excitation in both isotopes, with similar spectroscopic intensities associated with the second 2^+ state. In contrast to ^{100}Ru, however, an increase of the spectroscopy intensity is noted above 3.0 MeV in ^{98}Ru, the highest value being found for the pure $l=0$ excitation at 3.441 MeV. In both isotopes pure $l=2$ transitions to the 2_1^+ states were determined. For $l=2$ transfers, the strongest spectroscopic strength is associated, both in ^{98}Ru and ^{100}Ru, with the (4^+) states at 2.277 MeV and 2.394 MeV, respectively. The 2.394 MeV state presents about half of the spectroscopic $l=2$ intensity when compared to the 2.277 MeV state in ^{98}Ru, but both states have in common the fact that they are strongly excited in (p,p') inelastic scattering [16,17]. The 2.394 MeV level in ^{100}Ru has been pointed out in the literature as a possible hexadecapolar bandhead [17].

On the other hand, it is interesting to note that the spectroscopic strength (0.339) obtained in the present work for the population of the ^{98}Ru ground state is a factor of 1.9 higher than that obtained in the reanalysis of the Peterson *et al.* [5] data for the ^{100}Ru ground-state transition. This result is in disagreement with straightforward shell model expectations, pointing, thus, to a more complex structure. In fact, in the simple picture, starting from the $5/2^+$ ground states of ^{99}Ru and ^{101}Ru, which differ by one pair of neutrons, possibly in the same orbital, an equal or even smaller value of the spectroscopic strength would be expected for the ^{99}Ru$(d,t)^{98}$Ru transition. Furthermore, using the reanalysis of the (p,d) data, similar spectroscopic strengths were measured in the excitation of the ground and 2_1^+ states in ^{100}Ru, in contrast to the findings of the present work, where the ^{98}Ru ground state was shown to be more populated. No systematic trend can be pointed out for the $l=4$ excitations.

Globally taken, the excitation patterns associated with each l transfer in the pickup reactions on the Ru isotopes [1,5,6] are rather different in even and odd nuclei, even if an energy shift due to pairing is admitted. When starting from even targets, the strength is very much concentrated in some low-lying levels. Also, important $l=4$ transfers are detected in these reactions, while $l=4$ is missing in the pickup studies on the odd targets.

B. Total spectroscopic strengths

In this section, the information now available for the stable odd Ru isotopes is presented globally ($\Sigma G_{pick} = \Sigma C^2 S$) to infer the shell model occupancy in the ground states of the target nuclei. Shown in Table III are the sums, attributed to each l, of the extracted spectroscopic factors and, in the last column, the corresponding total strength detected. It is to be stressed that the totality of the strengths detected for each l transfer, even the doubtfully attributed ones, has been considered in the sums. These strengths represent in the ground states, respectively, the number of particles in each shell model orbital and the total occupancy number. Besides the results of the present work, Table III also shows the spectroscopic strengths presented in Ref. [5], those extracted in the reanalysis of the referred data of ^{101}Ru$(p,d)^{100}$Ru [5], and the values obtained with the ^{101}Ru$(d,t)^{100}$Ru [6] reaction.

Up to 3.5 MeV, approximately 41% of the total spectroscopic strength expected in comparison with five neutrons, available, in principle, in ^{99}Ru above the $N=50$ core, was detected. In contrast, the total spectroscopic strength obtained in the reanalysis of the ^{101}Ru$(p,d)^{100}$Ru reaction measured by Peterson *et al.* [5] up to 3.9 MeV, although also with a predominance of the $l=2$ component, corresponds to 1.63, representing only 23% of the limit value of 7. A lack of strength is also reported in the ^{101}Ru$(d,t)^{100}$Ru study [6] up to 2.40 MeV in which 18% of the limit was detected. It is worthwhile, however, to mention that the author [6] points out the presence of strong nonanalyzed $l=2$ transfers at higher excitation energies. These findings could indicate a less pronounced parentage of the ground state of ^{101}Ru with low energy states of ^{100}Ru, in comparison with that extracted for the pair ^{99}Ru and ^{98}Ru. A comparison of the sums of the spectroscopic strengths associated with each value of l, obtained by one-neutron pickup reactions, starting from odd (Table III) and even targets [1], shows considerable differences, especially with respect to the $1g_{7/2}$ orbital, for which much more strength is located in the ground state of even nuclei. In fact, almost all expected strength was found in the even targets ^{100,102}Ru while in ^{99,101}Ru more than half of it is lacking. Furthermore, in going from ^{99}Ru to ^{101}Ru, no increase in the target occupancy is verified for any of the valence orbitals, if the values of the reanalysis of ^{101}Ru$(p,d)^{100}$Ru are considered.

V. SUMMARY AND FINAL COMMENTS

This section summarizes the main conclusions of our study of the ^{99}Ru$(d,t)^{100}$Ru reaction which provided detailed information, previously unreported, on single-hole neutron strength distributions. The states at 2.365, 2.373, 2.409, 3.020, 3.046, 3.209 (possible doublet), 3.284 and 3.441 MeV were detected for the first time. Only transfers of $l=0$, 2, and 4 were measured and, although admixtures are allowed, several single l transfer were attributed. It is to be stressed that collective states, such as the 2_1^+, and some others which have been associated with multiphonon excitations in ^{98}Ru [14,15], were reached through only one or two values of l transferred, indicating strong single-hole parentage with the ground state of ^{99}Ru. Therefore, although some of those states may have a predominantly collective nature, the present study has shown that they contain significant two-quasiparticle components.

The $l=2$ spectroscopic strength is heavily concentrated in the transition to the state $(4)^+$ detected at 2.277 MeV, also strongly excited through inelastic scattering. This state probably corresponds to the state at 2.367 MeV in ^{100}Ru, considered a hexadecapolar bandhead [17]. The experimental information is a clear indication that, in the challenging $A\sim100$ region, only a part of the spectra of the even nuclei is expected to be reproduced by describing the nuclear structure considering exclusively an interacting boson representation. Further, the experimental spectroscopic factor here extracted for the transition to the ground state of ^{98}Ru is a factor of 1.9 higher than the strength obtained in the reanalysis of the ^{101}Ru$(p,d)^{100}$Ru (ground-state) reaction [5], characterizing a complexity beyond simple shell model predictions.

ACKNOWLEDGMENTS

This work was partially supported by the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), the Coordenação do Aperfeiçoamento de Pessoal de Nível Superior (CAPES), the Financiadora de Estudos e Projetos (FINEP), and the Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP).

[1] J. L. M. Duarte, T. Borello-Lewin, and L. B. Horodynski-Matsushigue, Phys. Rev. C **50**, 666 (1994).

[2] M. D. L. Barbosa, T. Borello-Lewin, L. B. Horodynski-Matsushigue, J. L. M. Duarte, G. M. Ukita, and L. C. Gomes, Phys. Rev. C **58**, 2689 (1998).

[3] J. L. M. Duarte, L. B. Horodynski-Matsushigue, T. Borello-Lewin, and O. Dietzsch, Phys. Rev. C **38**, 664 (1988).

[4] T. Borello-Lewin, J. L. M. Duarte, L. B. Horodynski-Matsushigue, and M. D. L. Barbosa, Phys. Rev. C **57**, 967 (1998).

[5] R. J. Peterson, R. A. Emigh, and R. E. Anderson, Nucl. Phys. **A348**, 8 (1980).

[6] F. C. Sampaio, M. Sc. dissertation, Instituto de Física da Universidade de São Paulo, 1981.

[7] C. M. Perey and F. G. Perey, At. Data Nucl. Data Tables **17**, 1 (1974).

[8] J. M. Lohr and W. Haeberli, Nucl. Phys. **A232**, 381 (1974).

[9] F. G. Becchetti and G. Greenlees, Phys. Rev. **182**, 1190 (1969).

[10] P. D. Kunz, computer code DWUCK4 (University of Colorado, Boulder, Colorado, 1974).

[11] R. H. Bassel, Phys. Rev. **149**, 791 (1966).

[12] L. B. Horodynski-Matsushigue and J. L. M. Duarte, Relatório de Atividades do Departamento de Física Experimental, Instituto de Física da Universidade de São Paulo, 1987, p. 108.

[13] B. Singh, Nucl. Data Sheets **84**, 565 (1998).

[14] J. Kern, P. E. Garrett, J. Jolie, and H. Lehmann, Nucl. Phys. **A593**, 21 (1995).

[15] A. Giannatiempo, A. Nannini, P. Sona, and D. Cutoiu, Phys. Rev. C **52**, 2969 (1995).

[16] E. H. du Marchie van Voorthuysen, M. J. A. de Voigt, N. Blasi, and J. F. W. Jansen, Nucl. Phys. **A355**, 93 (1981).

[17] S. Sirota, J. L. M. Duarte, L. B. Horodynski-Matsushigue, and T. Borello-Lewin, Phys. Rev. C **40**, 1527 (1989).